



Energy, Mines and
Resources Canada

Energie, Mines et
Ressources Canada

CANMET

Canada Centre
for Mineral
and Energy
Technology

Centre canadien
de la technologie
des minéraux
et de l'énergie

DESCRIPTION OF AN AUTOMATED, COMPUTER-BASED, CONTINUOUS MONITORING
SYSTEM FOR THE DETERMINATION OF THE SHORT-LIVED DECAY PRODUCTS OF
RADON AND THORON

J. BIGU

ELLIOT LAKE LABORATORY

APRIL 1983

23 pp

MINERALS RESEARCH PROGRAM
MINING RESEARCH LABORATORIES
DIVISION REPORT MRP/MRL 83-38 (TR)

DESCRIPTION OF AN AUTOMATED, COMPUTER-BASED, CONTINUOUS MONITORING
SYSTEM FOR THE DETERMINATION OF THE SHORT-LIVED DECAY PRODUCTS
OF RADON AND THORON

by

J. Bigu*

ABSTRACT

A portable, rugged, monitor has been designed and built for measuring the short-lived decay products of radon and thoron. The monitor is computer-based and employs a continuous filter strip which can be advanced at programmable time intervals to allow unattended continuous operation with automatic sampling, analysis and recording of radiation levels. Radionuclide analysis is carried out by two silicon diffused-junction alpha-detectors and electronic circuitry with multichannel spectral analysis capabilities. Standard gross α -count methods and α -spectroscopy methods can easily be implemented. The built-in computer performs a variety of operations via a specially designed interface module, including control and data recording functions, and computations, program storage and display functions. Programs and data are stored in the built-in cassette tape drive and the computer integrated CRT display and keyboard allow simple, prompted menu-type operation of standard software. Graphical presentation of α -spectra can be shown on the computer CRT and printed when required on the computer built-in thermal printer. In addition to implementing the specially developed radionuclide analysis software, the operator can interact and modify existing software, and program new ones, through BASIC language programming, or employ the computer in a totally unrelated, general purpose mode.

* Research Scientist and Radiation Project Leader, Elliot Lake Laboratory, CANMET, Energy, Mines and Resources Canada, Elliot Lake, Ontario.

CONTENTS

	<u>Page</u>
ABSTRACT	i
INTRODUCTION	1
DESCRIPTION OF THE RADON DAUGHTER/THORON DAUGHTER MONITORING SYSTEM	3
A. Detector System and Associated Electronic Circuitry	4
B. Filter Transport Mechanism	8
C. Filter	9
D. Pumping System and Pump Control	10
E. Computer System	10
COMPUTER PROGRAM STRUCTURE FOR THE RADON DAUGHTER/THORON DAUGHTER MONITOR	12
EXPERIMENTAL RESULTS	15
CONCLUSIONS	16
ACKNOWLEDGEMENT	18
REFERENCES	18

FIGURES

<u>No.</u>		
1.	View of radon daughter/thoron daughter continuous monitoring system	5
2.	Block diagram of radon daughter/thoron daughter continuous monitoring system showing main components of the system	6
3.	Computer program structure	13
4.	Alpha-spectrum from a radon daughter/thoron sample obtained with the radon daughter/thoron daughter monitor	17

INTRODUCTION

Radiation environments pose potential hazards to human health, hence, the need for adequate monitoring of radiation levels. Radiation monitoring is also important for engineering purposes such as the maintenance of reliable air quality control in working areas.

Monitoring of radiation levels is accomplished essentially by two different methods: a 'discrete' one normally known as grab-sampling, and a continuous method, generally referred to as continuous monitoring. Grab-sampling is conceptually simple and relatively inexpensive from the instrumentation point of view, but usually requires a great deal of manual operation which severely limits its capabilities. Continuous monitoring is considerably more complex instrumentally and analytically, but the automated nature of the sampling and the analysis processes makes it clearly preferable when large amounts of data are required, as is the case in a variety of engineering, industrial and research applications and for health physics purposes.

Monitoring of radon decay products, i.e., radon daughters, in uranium mines for dose exposure purposes is mandatory in Canada and in other countries. However, until recently, the contribution from thoron daughters to total dose exposure was usually ignored because their presence in uranium mines was assumed to be negligible. Recent data, however, indicate thoron concentrations in some locations to be much higher than originally thought or anticipated. Consequently, monitoring of thoron daughters in addition to radon daughters is both important and useful. Furthermore, the presence of thoron daughters interferes with the accuracy in the determination of radon daughter levels and, therefore, introduces errors in the calculation of dose exposure to occupational workers.

Although some continuous monitoring systems have been developed in

several countries, particularly the U.S.A. and Canada (1 to 8), this instrumentation has been mainly designed for radon and/or radon daughters. The need for an instrument and analytical procedures for monitoring radon daughters in the presence of thoron daughters is, therefore, important in view of the recent interest and emphasis placed on the potential health hazards associated with the inhalation of thoron daughters in uranium mines, mills and other radiation sites. Concurrent monitoring of radon daughters and thoron daughters is also useful as their relationship provides a good indicator of ventilation performance and sheds, in addition, light on other problems of considerable practical and theoretical importance.

In Canada, CANMET (Energy, Mines and Resources Canada) has taken a prominent role in the development of instrumentation for monitoring radon and thoron and their short-lived decay products in uranium mine environments, uranium tailings and in other uranium-related industries and radiation sites. Considerable development has been carried out both in-house and under contract with industry. This effort has resulted in a variety of monitoring instrumentation now in use in the country and abroad. One of these developments is the subject of this paper, and is a radon daughter/thoron daughter continuous monitoring system developed by Alpha-NUCLEAR (Toronto, Canada) under CANMET Contract and technical specifications. The system is now available under the name Model 750 continuous radon daughter/thoron daughter monitor. However, the flexibility of the system is such that it enables the analysis of practically any airborne α -emitter radionuclide, in addition to radon and thoron daughters.

DESCRIPTION OF THE RADON DAUGHTER/THORON DAUGHTER MONITORING SYSTEM

The Model 750 is a portable, radon daughter/thoron daughter monitoring system for the accurate measurement of individual radon daughter and thoron daughter concentrations and of their respective Working Levels. The system is computer-based and employs a continuous filter strip which can be advanced at programmable time intervals to allow individual sampling and analysis to take place with prompt read-out, or allow unattended continuous operation with automatic sampling, analysis and recording of radon daughter/thoron daughter data at prescribed time intervals to provide a long term trend record. Sampling is carried out through the filter, facing two α -detectors, by means of a servo-controlled suction pump with a flow rate of up to 12 L/min.

Radionuclide analysis is carried out by two silicon diffused-junction (DJ) detectors and associated electronic circuitry with α -spectroscopy capabilities. Thus, the DJ detectors can measure α -radiation either in gross counting mode, or with multichannel spectral analysis capability. Hence, any of the standard gross α -counting methods for determining the Working Level (WL) can be implemented (9 to 20) in addition to α -spectroscopy methods (21 to 24). Furthermore, decay time differentiation of radionuclides can be realized because of the dual detector configuration with a programmable delay time of up to 4 hours between successive readings. Thus, more accurate radon and thoron daughter analysis can be done using both α -spectroscopy and half-life discrimination.

The built-in computer performs a variety of operations via a specially designed interface, including control and data recording functions, and computation, program storage and display functions. Programs and data are stored in the built-in cassette tape drive and the computer integrated CRT display

and keyboard allow simple, prompted menu-type operation of standard software. Graphical presentation of α -spectra can be shown on the computer CRT and printed when required on the computer built-in thermal printer. In addition to implementing the specially developed radionuclide analysis software, the operator can interact and modify existing software through BASIC language programming, or employ the computer in a totally unrelated, general purpose mode.

The system is shock-mounted and housed in a weather-proof aluminum case, and is provided with battery back-up in the event of line power failures. Alternatively, the system can be operated from a 28 V DC power source.

A more detailed description of the different main components of the system is given below. A general view and a block diagram of the system are shown in Fig. 1 and 2, respectively.

A. DETECTOR SYSTEM AND ASSOCIATED ELECTRONIC CIRCUITRY

Two solid state, diffused junction (DJ) silicon detectors are used to measure alpha particles from decaying radionuclides collected in the filter. The detectors are not sensitive to beta or gamma radiation.

Detectors:	Diffused junction silicon;
Area:	400 mm ² ;
Hermetic Seal:	0.3 mil aluminized Mylar;
Energy Range:	2 MeV to 10 MeV. Threshold set at 2 MeV to eliminate noise and other unwanted radiation contributions;
Collimator:	A metallic honeycomb collimator is used to improve energy resolution;
Filter Diameter:	22 mm active filter diameter with screen backed support;
Detector-filter Gap:	about 5 mm;
Filter Seal:	O-ring seal mounted on linear actuator to provide hermetic seal during air sampling and release during filter advance;

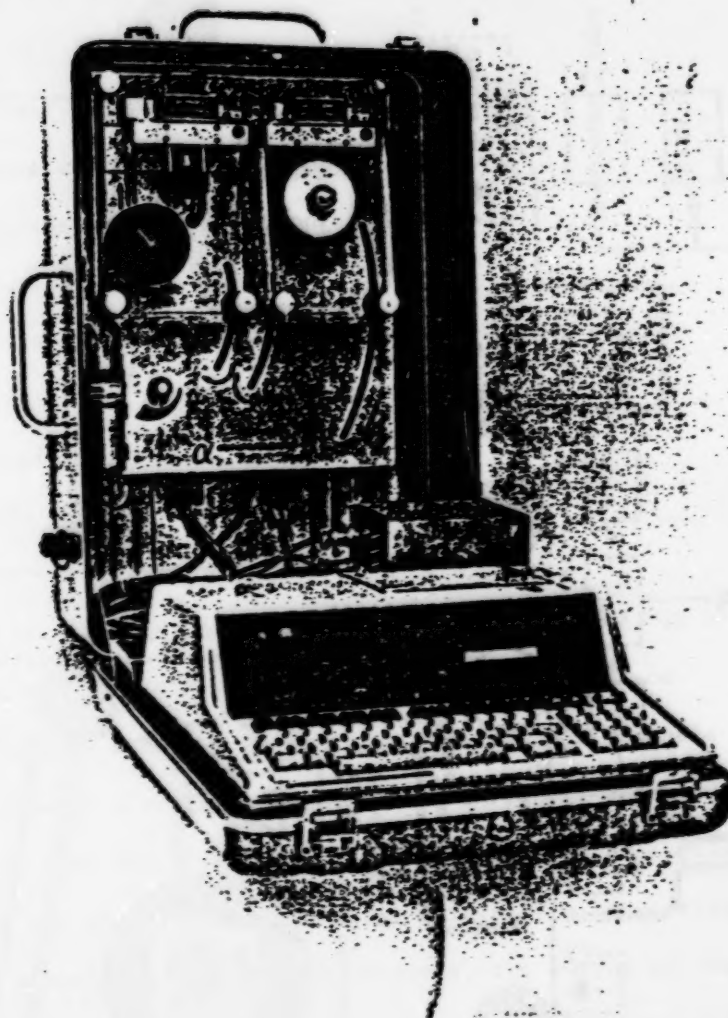


Fig. 1 - View of radon daughter/thoron daughter continuous monitoring system.

Fig. 2 - Block diagram of radon daughter/thoron daughter continuous monitoring system showing main components of the system.

Amplifier: Charge sensitive pre-amplifier and shaping amplifier;
 Analog to Digital Converter: 8 bit successive approximation, to give 256 channel spectrum with special software to give channel width compensation.

There are two multichannel analyzers (MCA), one per detector.

Each MCA consists of:

- a) Amplifier and threshold detector;
- b) Peak capture and hold;
- c) 10 bit successive approximation converter;
- d) 16 bit counter;
- e) 256 channels of 16 bit information stored in CMOS memory;
- f) Computer interface (shared between both MCAs);
- g) Control logic;
- h) Calibration circuit (shared between both MCAs).

Conversion time is 5 μ s.

Functionally, the MCA has four modes. Which mode the MCA is operating in, is set by the computer through a special computer interface.

The first mode consists of spectrum acquisition. Signals from the DJ preamplifier go through a combination amplifier threshold detector. If the signal is large enough, the threshold detector produces a 5 μ s pulse. This pulse is fed into the control logic where it initiates a conversion. The signal goes into a peak capture and hold circuit, the output of the circuit is fed into a 10 bit high speed analog to digital successive approximation converter (ADC). The most significant and least significant bit of this converter are not used. The 8 bit wide output of the converter is used to address one of 256 memory locations. The value at this memory location is loaded into a 16 bit counter. The counter is incremented by one and the result is stored back in the memory at this same location.

In the second mode the computer reads and clears the data from the memory. A 8 bit counter is used to address the memory in place of the ADC. The 16 bit channel count from the memory is fed to the computer 8 bits at a time, at the same time the memory location is cleared. The counter is incremented by one and the process is repeated until all 256 memory locations are read and cleared.

In the third mode, or standby mode, the α -counters are disabled and no action takes place.

The fourth mode consists of a calibration mode. The calibration circuit consists of the 16 bit digital to analog (DAC) converter. The data input to the DAC is a 16 bit counter. Controlled by the computer a relay switches the MCA input to the output of the DAC. The counter is incremented by one every 15 μ s. This creates a ramp at the output of the DAC. After each increment of the counter a conversion in the MCA is made, which results in 65536 (2^{16}) conversions. If each channel was of equal width there would be 256 counts per channel, but as the widths of each channel are not the same, channels that are wider than the mean widths will have greater than 256 counts while those narrower will have less than 256 counts.

The computer runs several calibration ramps and through software calculates the width of each of the 256 channels. The computer uses this information to test the function of the MCA, and to correct data for unequal channel widths.

B. FILTER TRANSPORT MECHANISM

A spool-mounted continuous filter strip is used to sample airborne particulates. The filter is advanced by two micro-processor controlled stepping motors, such that the first (radon daughter) analysis can take place according to the desired timing sequence. The filter then is advanced into a delay loop

with automatic slack take-up. A second stepping motor advances the sampled area to the second (thoron daughter) detector for subsequent analysis, a programmable time up to 4 hours later. The slack take-up mechanism provides for programmable time delays between readings, and also allows for timing lag in the event that a combination of methods with different timing sequences is used. The used filter is automatically wound onto a take-up spool at the end of the sequence.

An optical registration system is employed to accurately position the sampled area under the second detector to achieve a reproducible counting geometry. The optical system uses a solenoid actuated felt tipped pen to put a reference mark on the filter strip just before the first detector. An optical reading device immediately after the marker verifies that the mark has been made. A second optical reader mounted on the second detector in precisely the same relative configuration as the first, reads the mark when the filter completes the delay loop and uses it to accurately align the filtered area under the detector.

The transport mechanism has a moveable carriage which opens to allow easy threading of the filter strip. Microswitch interlocks monitor for carriage-open and maximum and minimum delay loop conditions.

The mechanical configuration of the detector and filter transport mechanism is such that it enables, if so desired, real-time α -counting, i.e., counting during the sampling period.

C. FILTER

Filter material:	Gelman Versapor 800, 0.8 μ m porosity;
Filter width:	35 mm;
Filter length:	25.6 m;
Spool diameter:	92 mm;

Active filter diameter:	22mm;
Filter advance:	38 mm per sample;
Leader:	A non-filter tape leader for threading purposes is included at the beginning and end of filter material;
End of tape detection:	The optical system senses and provides warning of end of filter material.

D. PUMPING SYSTEM AND PUMP CONTROL

The sampling pump is a high-efficiency, miniature rotary vane pump with a flow rate of up to 12 L/min and a 4×10^3 hour life time expectancy. The pump flow rate is servo-controlled using a thermistor bridge anemometer, $\pm 5\%$ accuracy. A computer signal is displayed should the pump fail to regulate. A microprocessor on command from the computer will start the air pump and regulate the air flow through the filter to 10 L/min. This is achieved through a servo-control loop consisting of a thermistor control anemometer depending on airflow frequency. At 200 hertz the airflow is 10 L/min. This frequency is measured by the microprocessor 8 bit timer/counter. The microprocessor is sending out a pulse width modulated frequency to the pump power supply. If the air flow is lower than 10 L/min the output frequency of the anemometer drops below 200 hertz, the microprocessor increases the pulse width going to the pump control, thus increasing the pump speed, hence increasing air flow. The damping of the servo control loop is done digitally by the microprocessor.

E. COMPUTER SYSTEM

The radon daughter/thoron daughter monitor uses a computer, Hewlett Packard Model 85, as the continuous monitoring system software control, data transfer and analysis and storage centre.

The HP-85 computer system is comprised of the following components:

- HP-85A computer, including 16 K memory;
- 82903A extra 16 K memory;
- 82936A ROM drawer;
- 00085-15003 I/O ROM;
- 82940A general purpose parallel input/output (GP-I/O) interface;
- 82939A serial interface.

The computer includes the following features and capabilities:

- BASIC programming with standard keyboard and extra numeric keypad;
- Eight user-definable special function keys;
- Built-in 5 inch (diagonal) CRT display with 32 character x 16 line capacity and 256 x 192 graphics resolution;
- Built-in tape cassette for program and data storage, 200 Kbyte capacity;
- Built-in thermal printer, 32 character width, graphics capability.

A microprocessor controlled logic interface executes the hardware control, timing, data acquisition and transfer functions on command from the main computer. This interface incorporates and executes the following functions:

- detector amplifiers;
- detector ADCs;
- memories - two 256 x 16 bit;
- optical marking system control;
- optical reading system;
- stepping motor control;
- linear actuator control;
- pump flow control;
- limit switch monitoring;
- power supplies.

The computer system interface communicates with the main computer through a two port GP-I/O interface.

The control microprocessor is an Intel 8741 microprocessor. It has 1024 x 8 EPROM and 64 x 8 RAM, 8 bit timer/counter and 18 programmable I/O pins all within a 40 pin integrated circuit (I.C) package.

COMPUTER PROGRAM STRUCTURE FOR THE RADON DAUGHTER/THORON DAUGHTER MONITOR

As indicated above, the main functions of the monitor are controlled by the computer. A computer program, the Auto Start Program, starts the system automatically when the power is turned on. It loads the Binary Program, which is a machine language program required by the system. It then prompts the user to enter the date and time. After the time is set, the Select Program Display allows the operator to select one of four operating programs:

1. The Instrument Program operates the sampling instrument. A Sampling Method is selected from a menu to control the pump and counter timing. A Channel Method is similarly selected to control the width of the window(s) over which the channel counts are to be integrated. The resulting integrated sample data are stored in Data Acquisition Files on a separate data cartridge.
2. The Analysis Program reads the raw sample data from the Data Acquisition Files and calculates radon and thoron daughter concentrations and Working Levels. The results are printed on the thermal printer.
3. The Editor Program permits the user to modify and/or create new Sampling Methods and Channel Methods.
4. The Calibrate Program is used to sample calibrated sources, rather than air. The pump and filter mechanisms are inactive, while counter timing is controlled from the keyboard. Data are not stored on tape, however, the spectrum is displayed, and may be copied to the printer.

The computer program structure is shown in block diagram form in Fig. 3. At present, the following methods are 'resident' in the Instrument

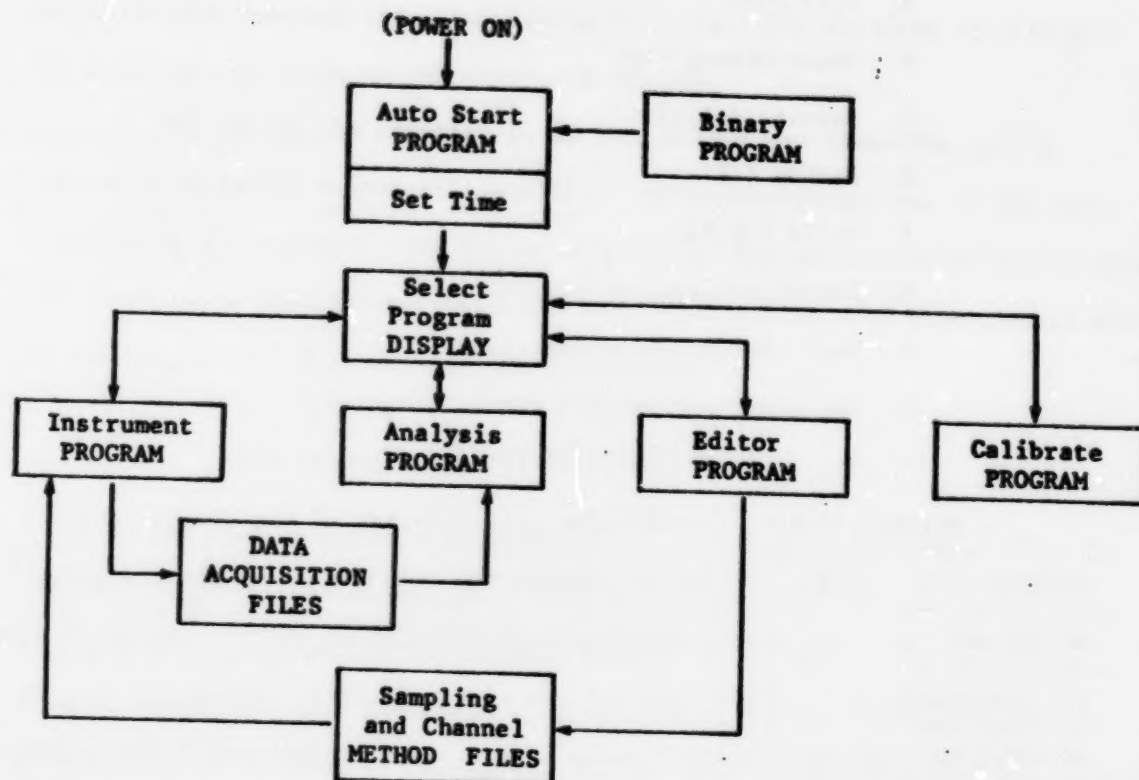


Fig. 3 - Computer program structure.

Program, which can be used on command:

1. Thomas-Tsivoglou (9,10,11)
2. Cliff (20)
3. Hill (17)
4. James-Strong (18)
5. Kusnetz (14,15)
6. Markov (16)
7. Rolle (12,13)
8. Alpha-spectroscopy (22,23)
9. Real time gross α -count (25)
10. One gross α -count for thoron daughters (25)
11. Two gross α -counts for thoron daughters (25)

Methods 10 and 11 enable the determination of the thoron daughter Working Level, $WL(Tn)$. Method 11 permits the calculation of the concentration of ThB and ThC, i.e., $[ThB]$ and $[ThC]$, in addition to $WL(Tn)$. Method 8 allows the determination of radon daughter and thoron daughter concentrations, in addition to their respective Working Levels, i.e., $WL(Rn)$ and $WL(Tn)$. The other methods indicated above are suitable for the determination of radon daughter data, as discussed in the pertinent literature. In these methods, α -counting of the sample by the second detector 4 hours after the end of sampling permits correction of radon daughter data collected in the presence of thoron daughters. The α -count by the second DJ detector is also used to determine $WL(Tn)$, as previously indicated.

At the end of the monitoring period, experimental data can easily be retrieved on the thermal printer by recalling the data file where the data were stored. The print-out shows the file name, the date (day, month, year), the time at which the sample was taken (hours, minutes, seconds) the sample

number, and the pertinent radionuclide data (concentration and WL) in tabular form. The data remain stored in the magnetic cassette tape for future use.

The α -spectrum of any one sample can easily be obtained by calling the Calibrate Mode and using the sample for α -spectrum analysis according to the procedure outlined in the Calibrate Program.

The use of the computer in an interactive way gives the user a virtually unlimited degree of flexibility which constitutes one of the main features of the monitor. The Editor mode allows new methods to be investigated and by suitable programming routines, long trend analysis of experimental data by adequate statistical methods can be realized.

EXPERIMENTAL RESULTS

The radon daughter/thoron daughter monitor has been tested in radon (thoron) daughter atmospheres in a large radon (thoron) calibration facility at the Elliot Lake Laboratory (CANMET, Energy, Mines and Resources Canada). Several tests have been conducted to determine the mechanical and electronic performance of the monitor and to verify the software that controls the functions of the instrument. In addition, measurements in the radon (thoron) facility have been carried out using different methods for determining WL(Rn), and other radiation data programmed in the computer. These data were compared with independent measurements by grab-sampling and by a radon daughter/thoron daughter continuous monitoring system operating on time integrating principles, with satisfactory results. Preliminary results show, however, that some improvement in the sampling inlet to reduce plate-out of decay products should be introduced.

The α -counting efficiency of the DJ detectors was determined with standard Am-241 sources. Efficiencies of about 20% and 5% were obtained

without and with collimator, respectively. Furthermore, spectrum analysis of samples shows that the energy linearity of the α -counting system including the MCA is better than 1%. Spectral resolution at half height full width (HHFW) from samples consisting of a mixture of radon daughters and thoron daughters were found to be about 5.2% for RaC' (7.69 MeV) and 3.5% for ThC' (8.78 MeV). A typical spectrum from a radon daughter/thoron daughter sample is shown in Fig. 4.

CONCLUSIONS

The monitor described in this paper is ideally suited for unattended environmental monitoring of the decay products of radon and thoron. It was originally conceived for monitoring radon (thoron) daughter radiation levels in underground uranium mines and other uranium-related industries. However, the instrument is quite flexible and could be used in the determination of radionuclides other than the above, provided adequate analytical procedures are developed or included in the already existing computer software. At present, the monitor enables full programming capabilities, therefore providing the user with a powerful research tool for theoretical and experimental work.

Since the instrument uses well established methods for the determination of radon and thoron progenies, its sensitivity is comparable to that of well designed, considerably simpler, and hence limited, grab-sampling systems. The only limitation is at present some decay products plate-out at the air intake which is rather difficult to eliminate because of the two DJ detectors and filter tape driving mechanism configuration used in this system.

The monitor is under extensive technical evaluation in order to improve its operation capabilities and mechanical configuration. A number of improvements have already resulted.

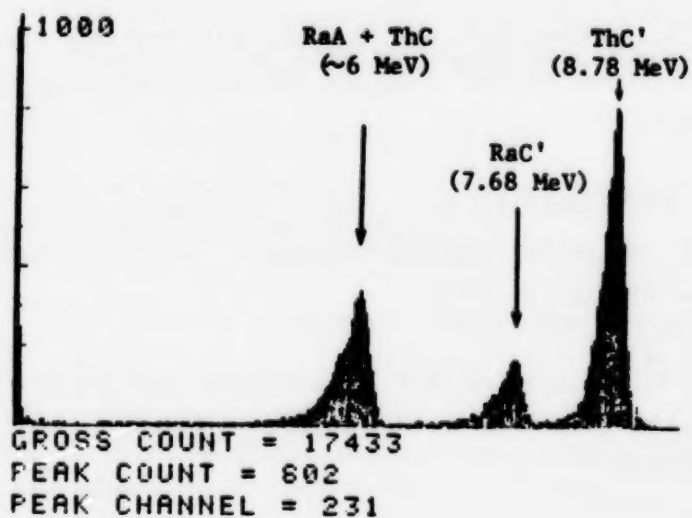


Fig. 4 - Alpha-spectrum from a radon daughter/thoron daughter sample obtained with the radon daughter/thoron daughter monitor.

ACKNOWLEDGEMENT

The author is grateful to Alpha-NUCLEAR staff for the technical input they have provided throughout this project. The radon daughter/thoron daughter continuous monitor has been developed under contract from CANMET (Energy, Mines and Resources Canada) to Alpha-NUCLEAR, Toronto.

REFERENCES

1. Harris, W.B., LeVine, H.D. and Watnick, S., "Portable radon detector for continuous air monitoring"; Am Ind Hyg Assoc Arch Ind Health, vol 16, p 493; 1957.
2. Franklin, J.C., Zawadski, R.J., Meyer, T.O. and Hill, A.L., "Data acquisition system for radon monitoring"; Report of Investigations 8100, U.S. Bureau of Mines; 1976.
3. Drouillard, R.F. and Holub, R.F., "Continuous working level measurements using alpha or beta detectors"; Report of Investigations 8237; U.S. Bureau of Mines; 1977.
4. Groer, P.G., Keefe, D.J., McDowell, W.F. and Selman, R.F., "Development of a prototype instant Working Level meter with automatic individual radon daughter readout"; Argonne National Laboratory Report PB-249 545 (BuMines OFR 19-76); Jan 1975.
5. Bigu, J., "A technical evaluation of the EDA radon gas continuous monitoring system"; Division Report MRP/MRL 79-42(TR); CANMET, Energy, Mines and Resources Canada; April 1979.
6. Thomas, J.W. and Countess, R.J., "Continuous radon monitor"; Health Physics vol 36, pp 734-738; 1979.
7. Larson, R.E. and Bressan, D.J., "Automatic radon counter for continual unattended operation"; Rev Sci Instrum vol 49, no 7, pp 965-969; 1978.

8. Aiken, J.H., Baker, E.G., Lee, J. and Tai-Pow, J., "Continuous and grab-sampling determinations of radon concentrations"; USERDA Report HASL-325; 1977.
9. Tsivoglou, E.C., "Qualitative description of successive transformations in atmospheric samples"; Dissertation; Ohio State University; 1953.
10. Tsivoglou, E.C., Ayer, H.E. and Holaday, D.A., "Occurrence of non-equilibrium atmospheric mixtures of radon and its daughters"; Nucleonics, vol 11, no 9, pp 40-45; 1953.
11. Thomas, J.W., "Measurement of radon daughters in air"; Health Physics, vol 23, pp 783-789; 1972.
12. Rolle, R., "Improved radon daughter monitoring procedure"; Am Ind Hyg Assoc J, pp 153-160; March/April 1969.
13. Rolle, R., "Rapid Working Level monitoring"; Health Physics, vol 22, pp 233-238; 1972.
14. Kusnetz, H.L., "Radon daughters in mine atmospheres"; Am Ind Hyg Assoc J, vol 17, p 1; 1956.
15. Kusnetz, H.L., "Radon daughters in mine atmospheres - a field method for determining concentrations"; Ind Hyg Quarterly; March 1956.
16. Markov, K.P., Ryabov, N.V. and Stas, K.N., "A rapid method for estimating the hazard associated with the presence of radon daughter products in air"; At Ehnerg, vol 12, p 315; 1962.
17. Hill, A., "Rapid measurement of radon, decay products, unattached fractions and Working Level values of mine atmospheres"; Health Physics, vol 28, no 4, pp 472-474; April 1975.
18. James, A.C. and Strong, J.C., "A radon daughter monitor for use in mines"; Proc 3rd Int Congr IRPA, Washington, USAEC Conf 730907-P2, pp 932-938, Sept. 9-14, 1973.

19. Rock, R.L., Sampling mine atmospheres for potential alpha energy due to the presence of radon-220 (thoron) daughters"; MESA Informational Report IR-1015, U.S. Dept. of the Interior; 1975.
20. Cliff, K.D., "The measurement of low concentrations of radon-222 daughters in air, with emphasis on RaA assessment"; Phys Med Biol, vol 23, no 1, pp 55-65; 1978.
21. Martz, D.E., Holleman, D.F., McCurdy, D.E. and Schiager, K.J., "Analysis of atmospheric concentrations of RaA, RaB and RaC by alpha spectroscopy"; Health Physics, vol 17, pp 131-138; 1969.
22. Tremblay, R.J., Leclerc, A., Mathieu, C., Pepin, R. and Townsend, M.G., "Measurement of radon progeny concentration in air by α -particle spectrometric counting during and after air sampling"; Health Physics vol 36, pp 401-411; 1979.
23. Cote, P., Carson, D.W., Leclerc, A., Townsend, M.G. and Tremblay, R.J., "Optimization of radon and thoron daughter counting procedures"; Division Report MRP/MSL 78-201(J); CANMET, Energy, Mines and Resources Canada; 1978.
24. Kerr, G.D., "Measurement of radon progeny concentrations in air by alpha-particle spectrometry"; Oak Ridge, Technical Report ORNL-TM 4924; 1975.
25. Bigu, J., Unpublished data.

